LBL-19488

COLLECTIVE EFFECTS AND LATTICE IMPLICATIONS FOR AN FEL BYPASS RING*

J. Bisognano, A. Jackson and M.S. Zisman

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

May 1985

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

COLLECTIVE EFFECTS AND LATTICE IMPLICATIONS FOR AN FEL BYPASS RING*

J. BISOGNANO, A. JACKSON, and M.S. ZISMAN
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Introduction

Optimizing the performance of a single-pass free electron laser (FEL) in a storage ring requires a stored beam having both a relatively high volume density and a low momentum spread. These requirements place severe constraints on storage ring design due to the impact of both coherent and incoherent multiparticle phenomena. In this paper we present approximate scaling laws that elucidate the relative importance of various lattice parameters, and we will describe a systematic approach (embodied in the computer code ZAP) to parameter selection.

Figure of Merit for FEL Operation

To facilitate optimization of a storage ring for FEL purposes, it is desirable to define a "figure of merit." The one-dimensional theory of high-gain FEL operation predicts exponential growth and a saturation power level. In designing a storage ring to serve as an FEL, it is clearly desirable to operate close to the saturation limit. Furthermore, it is important to minimize the required length of undulator used to reach this output power level.

From one-dimensional theory we know that, in the exponential-growth regime, the laser power grows with distance, z, at a rate corresponding to [1]:

$$P = \frac{P_0}{9} e^{z/\ell_e} \tag{1}$$

where the e-folding length is defined as

$$\ell_e = (\lambda_u/\rho)/(4\pi\sqrt{3}) \ . \tag{2}$$

At saturation, the peak power and saturation length are given (for zero energy spread) by [1]:

$$z_{sat} \approx (\lambda_u/\rho) \tag{3}$$

and

$$P_{sat} \approx \rho \, P_{beam} \tag{4}$$

In these expressions the FEL gain parameter, ρ, scales as [1]:

$$\rho \sim \left[\frac{\lambda}{\gamma^2} \frac{\hat{I}}{\sqrt{\epsilon_x \epsilon_y}}\right]^{1/3} \tag{5}$$

where λ is the FEL wavelength. Thus, maximizing the output power and minimizing the saturation length both correspond to maximizing the parameter ρ.

If the effects of non-zero beam energy spread are taken into account, the growth rate is reduced significantly (and hence the saturation length increased) for $\sigma_p/\rho \gtrsim 1$, where $\sigma_p = (\delta p/p)_{rms}$. In the regime studied here, we find typical ρ values of 10^{-3}, so we have allowed $\sigma_p = 2 \times 10^{-3}$ as an upper limit for the momentum spread.

In summary, it appears that the FEL gain parameter ρ and the e-folding length ℓ_e represent the most suitable figure of merit.

Coherent Instabilities and Machine Impedance

The interaction of the beam with its environment can generate a variety of coherent instabilities that limit the achievable beam current. The electromagnetic fields are generated via beam interactions with the RF cavities, vacuum chamber discontinuities, and the wall resistivity. In addition, the emission of synchrotron radiation produces fields that can affect beam stability.

The effective longitudinal (Z/n) and transverse ($Z_\perp$) impedances are averages of the full frequency dependent impedances over the bunch mode spectra. For the longitudinal impedance, we have assumed a model consistent with SPEAR measurements [2]. For bunch lengths smaller than the effective beam pipe radius b this model gives

$$\left(\frac{Z}{n}\right)_{eff} = \left(\frac{Z}{n}\right)_0 \left(\frac{\sigma_\ell}{b}\right)^{1.68} \tag{6}$$

and potential well distortion effects are assumed negligible. With a smooth vacuum chamber design, a small storage ring may be expected to have an impedance of $(Z/n)_0 = 1$ to 2 ohms.

For small storage rings there is another important source of interaction of the beam, that with the radiation it has generated. This effect has been found to be well approximated, for several geometries, by an impedance of the form [3]

$$\frac{Z}{n} = 300 \left(\frac{b}{R}\right) \left(\frac{\theta}{2\pi}\right) \quad [\Omega] \ . \tag{7}$$

(For a closed vacuum pipe, the frequency dependence is of the resonant type, and Eq. (7) gives a rough smeared out average value.)

For smooth, small rings, this "free-space" impedance may set a lower limit on the attainable longitudinal impedance. The bend angle θ in Eq. (7) is just 2π for the standard dipoles in a ring, but can take on a much larger value for a ring having damping wigglers.

It is important to note that, while the instability driven by the free-space impedance has probably been observed in electron ring (ERA) experiments, there is no quantitative information available regarding the dependence of the instability on bunch lengthening, momentum spread stabilization, etc. The lack of experimental evidence is probably due to the fact that no existing storage ring is dominated by this source of impedance. Clearly, more theoretical work is required. For the purposes of this paper, we take the conservative view that the longitudinal impedance cannot fall below the value due to the free-space impedance.

Given the impedance estimates above, the threshold peak current values for longitudinal and transverse single bunch instabilities are given, respectively, by

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE AC03 76SF00098.

$$\hat{I}_L = \frac{2\pi\, \alpha\, \sigma_p^2\, (E/e)}{(Z/n)\mathrm{eff}} F_L \tag{8}$$

$$\hat{I}_T = \frac{4\sqrt{2\pi}\, \nu_s\, (E/e)}{Z_T \bar{\beta}\, \sigma_{\ell/x}} F_T \tag{9}$$

where $x = \max(b, \sigma_\ell)$ and the form factors F are both of the order of unity. For lattices considered for the FEL bypass ring, the longitudinal instability is found to have the lower threshold. The conflict between a high peak current and a small momentum spread is immediately obvious.

Intrabeam Scattering

Multiple Coulomb scattering of electrons within a beam bunch causes both longitudinal and transverse diffusion. The beam emittances will reach equilibrium when the intrabeam scattering (IBS) and quantum excitation rates are balanced by the radiation damping rate.

The theory of multiple IBS has been developed most fully in References [4] and [5]; the latter formulation is used in ZAP. Although detailed results of the theory require numerical evaluation of rather complicated integrals, we will concentrate here on the basic physical principles.

In the beam frame, the horizontal momentum spread typically exceeds the longitudinal, and IBS predominantly transfers momentum from the horizontal to longitudinal dimension. In dispersive regions, however, the longitudinal momentum changes excite horizontal betatron oscillations and these may dominate (in terms of beam size) the original loss in horizontal momentum. For the typical small synchrotron radiation lattices we have looked at, the horizontal diffusion rate is the most important cause of transverse emittance growth. The so-called H-function

$$H = \gamma_x \eta^2 + 2\alpha_x\, \eta\eta' + \beta_x \eta'^2 \tag{10}$$

is the most critical parameter for the transverse diffusion.

For the class of lattices considered here, the horizontal diffusion rate was found to be given approximately by

$$\frac{1}{\tau_x} = C \frac{\hat{I}}{\sigma_p\, \gamma^3\, \epsilon_x^2} \left\langle \frac{H^{1/2}}{\beta_y^{1/2}} \right\rangle \tag{11}$$

where $C = 10^{-9}$ m /(A-sec) for a 10:1 emittance coupling. (Note: Eq. (11) is intended only to illustrate the characteristic dependence on the various parameters. Evaluation of the full formulae is required for actual design calculations.) We see from Eq. (11) that large $\hat{I}$ and H (dispersion), small emittance and momentum spread, and small β_y (high vertical density) all tend to increase the diffusion rate. Typically, a horizontal emittance of 10^{-8} m-rad yields diffusion times of tens of milliseconds at an energy of 750 MeV and a peak current of a few hundred amperes. For typical cases we find that the equilibrium emittance is given approximately by

$$\epsilon_x \approx \frac{1}{2} \left[\epsilon_{0x} + \sqrt{\epsilon_{0x}^2 + \frac{C\hat{I}}{\sigma_p \gamma^3\, g_{SR}} \left\langle \frac{H^{1/2}}{\beta_y^{1/2}} \right\rangle } \right] \tag{12}$$

We note that when the equilibrium emittance, Eq. (12), is dominated by IBS growth, the optimization factor becomes

$$\frac{\hat{I}}{c} \sim \sqrt{\frac{\alpha}{H^{1/2}}}$$

In the smooth approximation $H^{1/2}$ and α are proportional, and the dependence on α vanishes.

Touschek Scattering

Single, large-angle Coulomb scattering may lead to a momentum error for the electron that exceeds the machine acceptance. Particles lost by this Touschek scattering mechanism lead to a reduction of the beam lifetime.

The Touschek scattering lifetime, is given by [6]

$$\frac{1}{\tau} = \frac{\pi\, r_e^2\, c\, N_b}{\delta p_x\, (\Delta p_{RF})^2\, V_p}\, C(\mu) \tag{13}$$

where V_p is the bunch volume, μ is defined as

$$\mu = \left(\frac{\Delta p_{RF}}{\gamma \delta p_x}\right)^2 \tag{14}$$

and $C(\mu)$ is the function

$$C(\mu) = \int_1^\infty (2x - \ln x - 2)\, \frac{e^{-\mu x}}{2x^2}\, dx\ . \tag{15}$$

In the parameter regime of interest for FEL rings, the function $C(\mu)$ scales roughly as $1/\sqrt{\mu}$. Thus, the Touschek lifetime scales like the cube of the momentum acceptance.

In averaging the bunch volume and the transverse momentum spread over an actual lattice, the effects of the dispersion should be included. Including dispersion, the horizontal size, σ_x, is increased by the factor

$$\sqrt{1 + \frac{\eta^2 \sigma_p^2}{\beta_x \epsilon_x}}$$

and the rms transverse momentum spread is increased by the factor

$$\sqrt{\frac{\eta^2\sigma_p^2 + \beta_x^2\, \sigma_p^2\, \phi^2 + \beta_x \epsilon_x}{\eta^2 \sigma_p^2 + \beta_x \epsilon_x}}$$

where

$$\phi = \eta' + \frac{\alpha_x \eta}{\beta_x}\ .$$

Computation of Collective Effects - ZAP

The actual behavior expected from a particular lattice configuration must be investigated via explicit calculations of the relevant collective effects. To allow such calculations for the FEL rings of interest to this study, development of a new computer code called ZAP has begun [7]. When completed, it is envisioned that ZAP will allow the preliminary evaluation of the machine performance and parameters of any storage ring.

As primary inputs, ZAP utilizes the parameters of a lattice along with the relevant "physics" needs (e.g., the FEL requirement for small momentum spread). The code then calculates, as a function of rms bunch length, the required RF voltage and corresponding bucket height. Impedance estimates are also made and threshold currents are calculated. From these threshold current values and the radiation damping time, ZAP calculates the intrabeam scattering (IBS) rates and iterates to find the equilibrium emittance. Finally, this equilibrium emittance value and a selected RF bucket height are used to obtain the Touschek lifetime of the ring.

Other options of the code include calculation of the primary FEL parameters, gas scattering lifetime, and estimates of multibunch instability growth rates and frequency shifts.

In this paper, we standardized on the 500 MHz RF cavity used in PETRA. The required number of RF cells is estimated (assuming 500 kV/cell) based on the voltage needed to maintain a beam of the chosen momentum spread and bunch length within the linear part of the bucket. Thresholds for the longitudinal and transverse single-bunch instabilities are then calculated based on Eqs. (8) and (9).

Calculations for a given lattice are carried out at many lattice points. ZAP evaluates the three growth rates (horizontal, vertical, longitudinal) and then computes the overall growth rate in each dimension averaged over the entire ring. This calculation is iterated to find the equilibrium emittance.

As for the IBS case, the Touschek calculation is performed at each lattice point and the average lifetime for the ring computed. The input value for the momentum acceptance should properly be interpreted as the smallest of the bucket height, the dynamic aperture, or the physical aperture.

The code described here has been written for a VAX-11/780 computer. A complete calculation (without iteration) of the IBS and Touschek lifetimes for a lattice having 146 lattice points requires less than 20 seconds of VAX CPU time.

Results

ZAP has been used to calculate the peak current and equilibrium emittances of five different lattices to estimate the FEL parameter ρ. The parameter variations with energy for one such lattice are shown in Fig. 1. It is clear that basically everything follows the pattern dictated by the emittance values. For an FEL operating at 400 A an electron beam energy of 750 MeV is close to optimum.

The five lattices evolved from a design 180 m in circumference with relatively large α (derived from low field bending magnets) to maximize the peak current achievable when the momentum spread is allowed to increase to 0.002 under the influence of the microwave instability. The structure of the lattice is the well-known Chasman-Green type with high field electromagnetic wiggler magnets to improve the radiation damping. The next two lattices investigated were shorter versions (130 m) of the original structure with higher field bending magnets and correspondingly lower momentum compaction. In one case, the damping wigglers were removed. The final two lattices we investigated were varieties of a hybrid combined-function structure first proposed by Vignola [8] for a 6 GeV light source.

The results of these studies indicate that, over the range of lattices studied, there is less than a 40% reduction in ρ compared with the best (original) structure. Because the performance of the hybrid combined function lattices is degraded by only 20%, it is one of these structures that has been chosen for more detailed analysis [9].

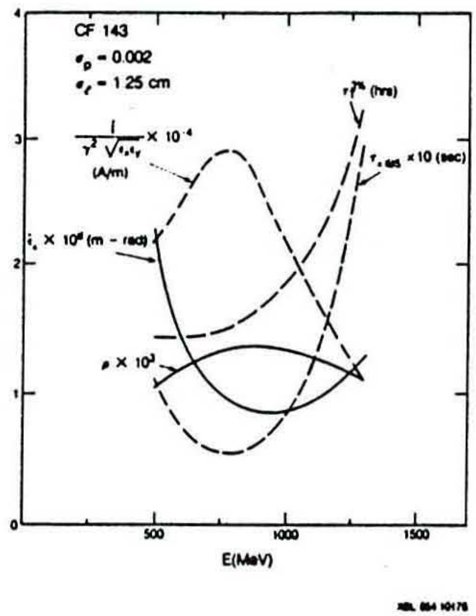

Fig. (1) Energy dependence of the intrabeam scattering lifetime, Touschek lifetime (for a 3% acceptance), equilibrium emittance, current density, and FEL gain parameter for a representative lattice.

References

[1] J. Bisognano, et al., "Feasibility Study of a Storage Ring for a High-Power XUV Free Electron Laser," submitted to Particle Accelerators.

[2] A. Chao and J. Gareyte, PEP Note-224, 1976.

[3] A. Faltens and L.J. Laslett, BNL-20550, p. 486, 1975.

[4] A. Piwinski, IXth Intl. Conf. on High Energy Accelerators, Stanford, 1974, p. 405.

[5] J. Bjorken and S. Mtingwa, Particle Accelerators 13, 115 (1983).

[6] H. Bruck, Circular Particle Accelerators, LANL Report No. LA-TR-72-10 Rev.

[7] Computer code ZAP, written by M.S. Zisman, J. Bisognano, and S. Chattopadhyay, unpublished.

[8] G. Vignola, BNL-35678.

[9] A. Jackson, et al., "A Lattice and Bypass Design for a Coherent XUV Facility," these proceedings.